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SCIENTIFIC REPORTS

VOLUME II. No. 1

REPORT ON THE METEOROLOGICAL OBSERVATIONS

BY

JAMES PATON, M.A., B.Sc.

WITH NINE TEXT-FIGURES

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THE observations, on which the following report is based, fall into two series :

I. Throughout the course of the John Murray Expedition meteorological observations were taken at four-hourly intervals on the "Mabahiss"; Dr. H. Faouzi, Director of Fishery Research, Egyptian Coastguard and Fishery Service, was in charge of these observations throughout the whole period and from 8 a.m. to 8 p.m. inclusive they were taken by him personally, while at midnight and at 4 a.m. they were taken by the officer of the watch, who was on duty.

The observations taken were as follows :

(*a*) Height of the barometer.
(*b*) Air temperature, dry and wet bulb.
(*c*) Sea surface temperature.
(*d*) Wind direction, observed.
Wind force in miles per hour.
(*e*) Ship's course.
(*f*) Ship's speed.

The observations on the wet-bulb thermometer were not taken at midnight or at 4 a.m., and items (*e*) and (*f*) were obtained from the ship's log.

The "Mabahiss" was supplied on loan by the Meteorological Department of the Air Ministry, London, with an Assmann psychrometer and a cup-anemometer with electrical recording apparatus. The anemometer was fitted to an upright above the awning on the upper navigating bridge and the recorder was situated in the wheel-house. The position at which observations were taken by means of the Assmann psychrometer varied according to circumstances. Every effort was made to select a site where the temperature readings would not be affected by radiation from bulkheads or heating from the

engine-room, while at the same time avoiding, so far as was possible on such a small vessel, any possibility of spin-drift settling on the dry-bulb thermometer. Observations of the sea-surface temperature were taken by collecting the surface-water sample in a leather or wooden bucket and placing the thermometer in the bucket as soon as the sample reached the deck.

II. Thanks to the kind offices of the Meteorological Department of the Air Ministry, London, it was arranged that observations on the sea-surface temperature, and the wind direction (true) and wind force, should be made by a number of ships of the British Merchant Service throughout the whole year from September, 1933, to September, 1934, along three routes, namely :

(i) Between Aden and Karachi.

(ii) Between Aden and Bombay.

(iii) Between Aden and Colombo, or, in the case of vessels not actually calling at this latter point, between Aden and long. 80° E.

The vessels which volunteered for this work, were supplied with a standard pattern thermometer, and the observations were taken at 4-hourly intervals (apparent time) by the officer of the watch.

In addition to the above three series of observations, a fourth series was very kindly carried out by arrangement with the British India Steam Navigation Co. Ltd. between Bombay and Mombasa.

§1. Wind.

The observations were made in the Indian Ocean from the beginning of November until the end of April, and the normal conditions in the NE. monsoon, the steady moderate breeze, were experienced. There is no indication of the 12-hourly variation in velocity observed in the Atlantic by the " Challenger " Expedition.

§2. Humidity.

The mean humidity over the open sea increased from about 75% in the North Arabian Sea to over 80% in the South, and the normal slow increase towards the end of the monsoon period was observed. Single observations of humidity greater than 90% were infrequent.

§3. Sea Surface Temperatures.

In addition to the sea surface temperature observations of the " Mabahiss ", similar observations at the same hours were taken by ships of the British Merchant Navy in connection with water sampling in the Arabian Sea. In Vol. V, 1928, of the ' Marine Observer ', are given monthly mean sea temperatures for areas of 2° of longitude by 2° of latitude computed from observations taken between 1855 and 1917. These have been used for the purpose of comparison, to show any marked deviations from the normal sea surface temperature distribution which may have occurred during the period of the Expedition. It will be obvious that local temperature variations will not be shown in such comparisons over areas as large as 2° squares.

The table given below is for the voyage of the " Mabahiss " :

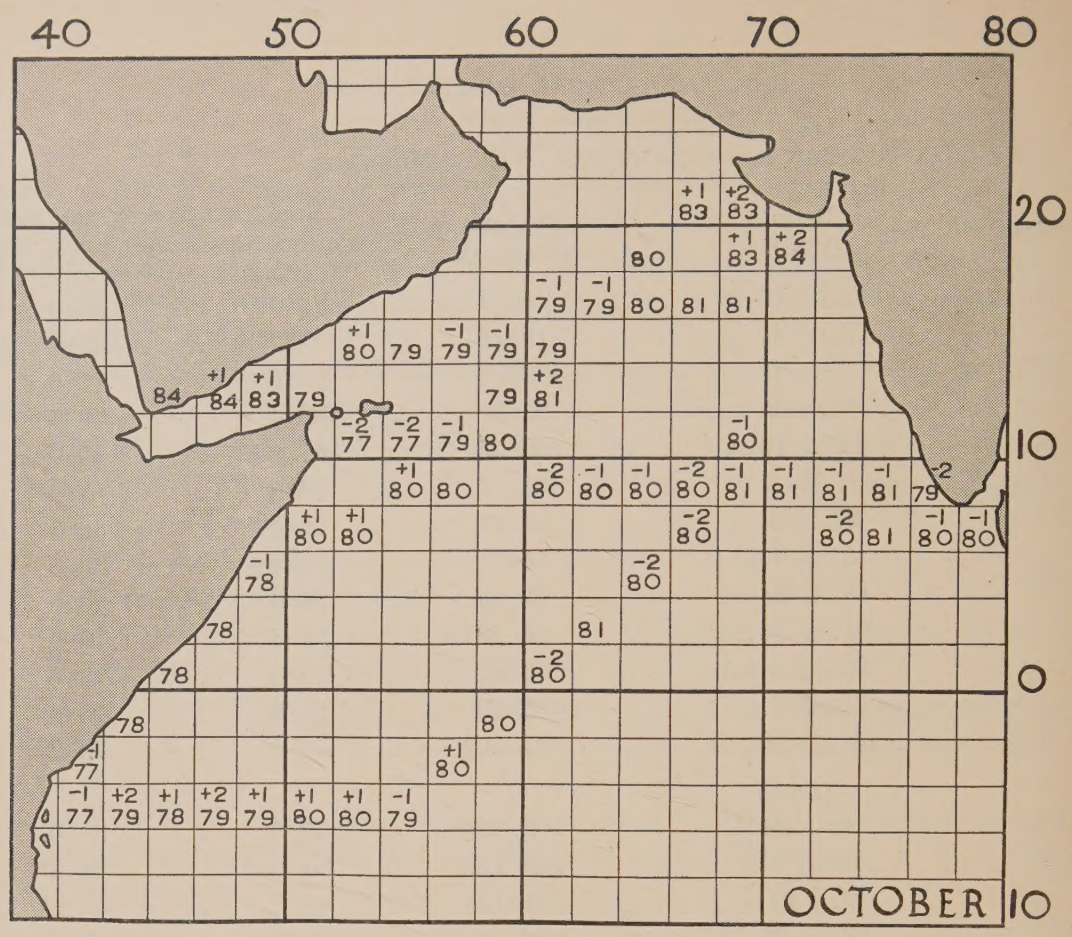
Cruise.	Dates (1933).	Positions (Stations).	Mean temperatures (° F.).	Approximate normal temperature (' Marine Observer ' (° F.).
I.	13.ix–18.ix	5–11	88·4	89·0
	19.ix–21.ix	12–18	85·5	85·0
II.	5.x–8.x	22	73·6	77·0
	9.x–12.x	23–29	82·4	79·0
	14.x–15.x	32–33	81·5	80·0
	16.x	34–35	84·8	83·0
III.	24.x–2.xi	38–53	79·5	80·0
	4.xi–9.xi	55–61	80·6	80·0
IV.	18.xi–21.xi	62–65	78·8	79·0
	24.xi–28.xi	68–75	78·8	78·0
	29.xi–3.xii	76–82	79·2	78·0
	4.xii–7.xii	83–90	80·6	78·6*
V.	14.xii–30.xii	91–102	79·5	79·0*
	(1934.)			
VI.	11.i–24.i	103–126	79·7	81·0
VII.	31.i–5.ii	127–129	81·5	82·4*
	9.ii–21.ii	131–135	81·7	82·0*
VIII.	18.iii–25.iii	135–139	83·5	83·0
	10.iv–12.iv	162–165	85·6	84·5
IX.	20.iv–30.iv	166–173	84·0	84·0*
	1.v–4.v	175–184	83·1	82·4
	5.v–7.v	185–194	83·8	83·5
X.	14.v–15.v	199–202	84·2	85·0
	16.v–17.v	203–209	83·5	84·4

* Open seas.

Except for local variations in the currents off Cape Guardafui (Stations 22–29), temperatures over the sea in coastal areas show no great deviations from normal. Approximately normal temperatures, too, were encountered by the " Mabahiss " in the open sea in all areas except at the head of the Arabian Sea (Stations 83–90), where the waters appear to have been appreciably warmer than is usual at this time of year.

The charts of mean sea temperature for the months October, 1933–May, 1934 have been prepared from data supplied by the Merchant Navy. All deviations from normal temperature as given in the ' Marine Observer ' are inserted above the actual mean temperature for the month for each square. When no data for comparison are available the figure has been ringed.

Deviations of 1° F. in these charts are not very significant, as each mean given is the average of from 3 to at the most 12 sets of observations. The values for areas in the region of 10° N. latitude, the most frequented part of the Arabian Sea, are the most reliable. In October, 1933, and January, February and March, 1934, sea temperatures in this region tended to be slightly below normal. The chart for December, when many observations were available, shows clearly the NE.–SW. direction of the isotherms following the set of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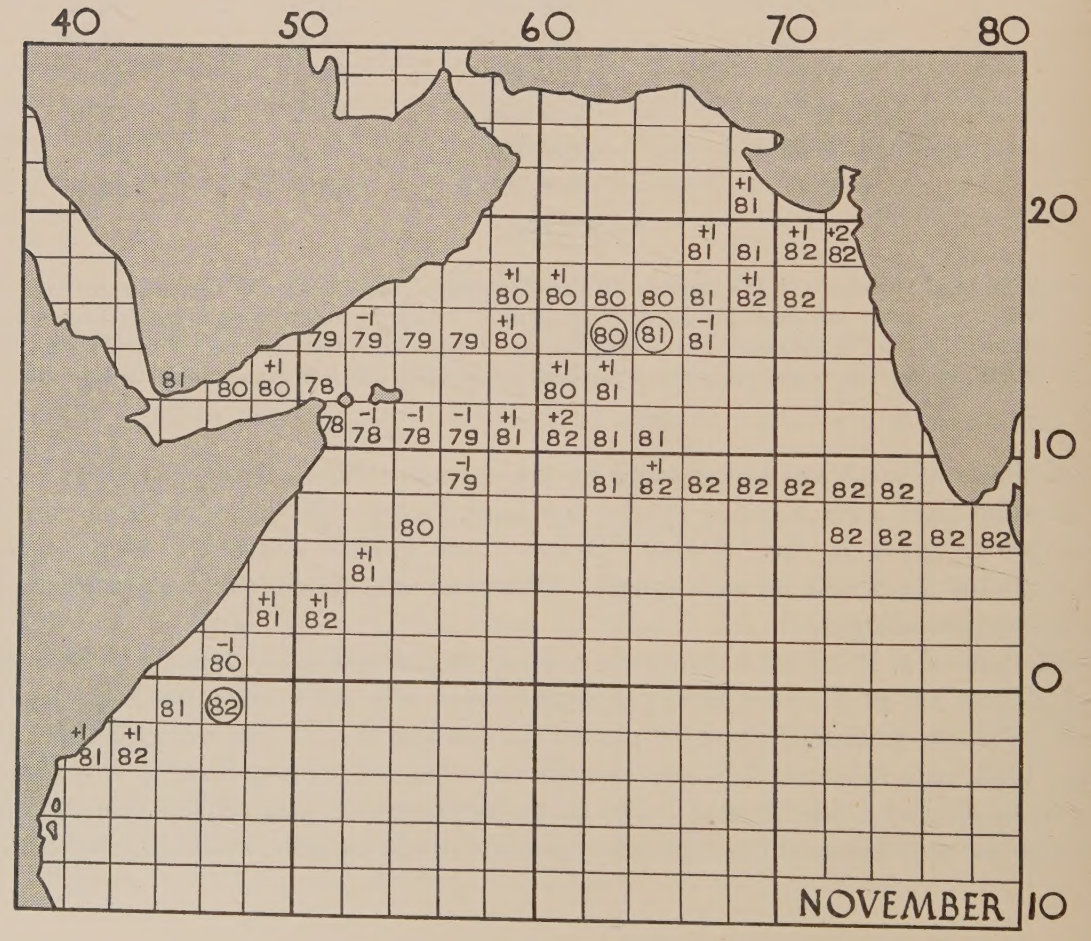
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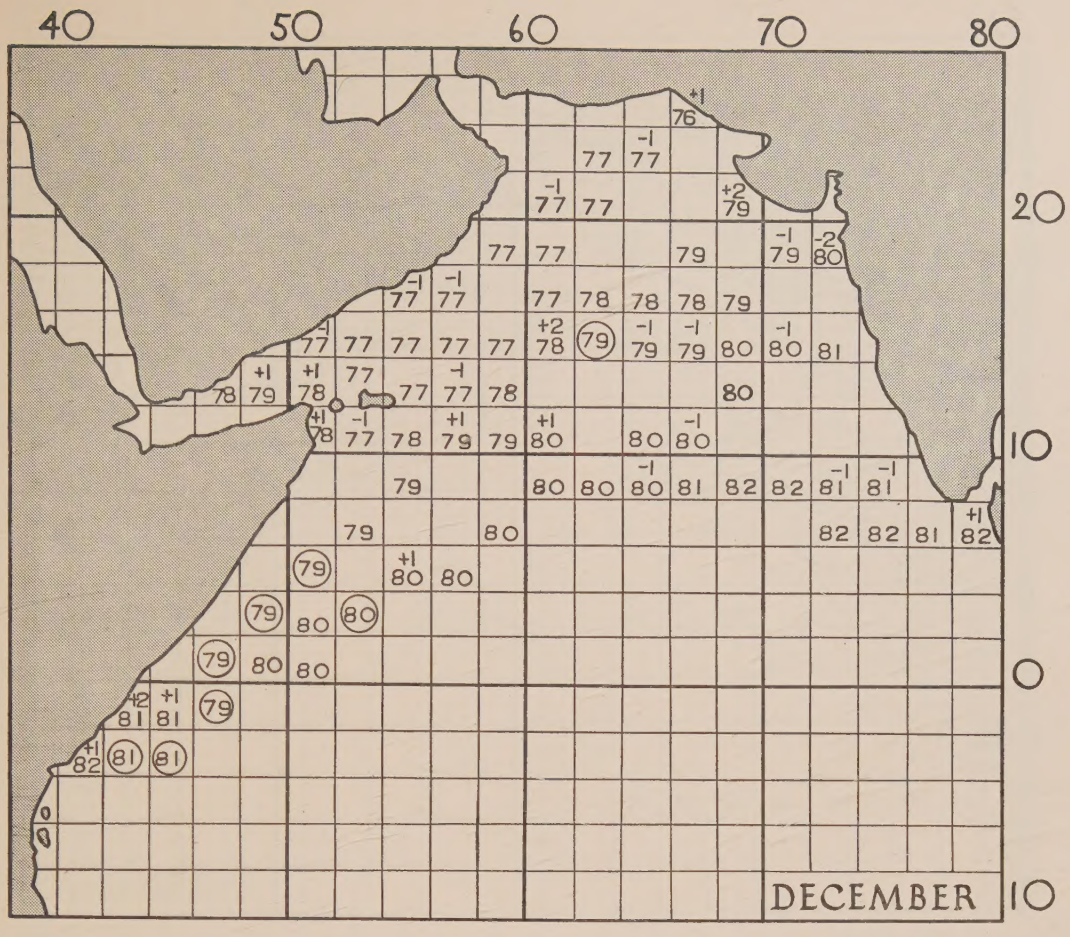
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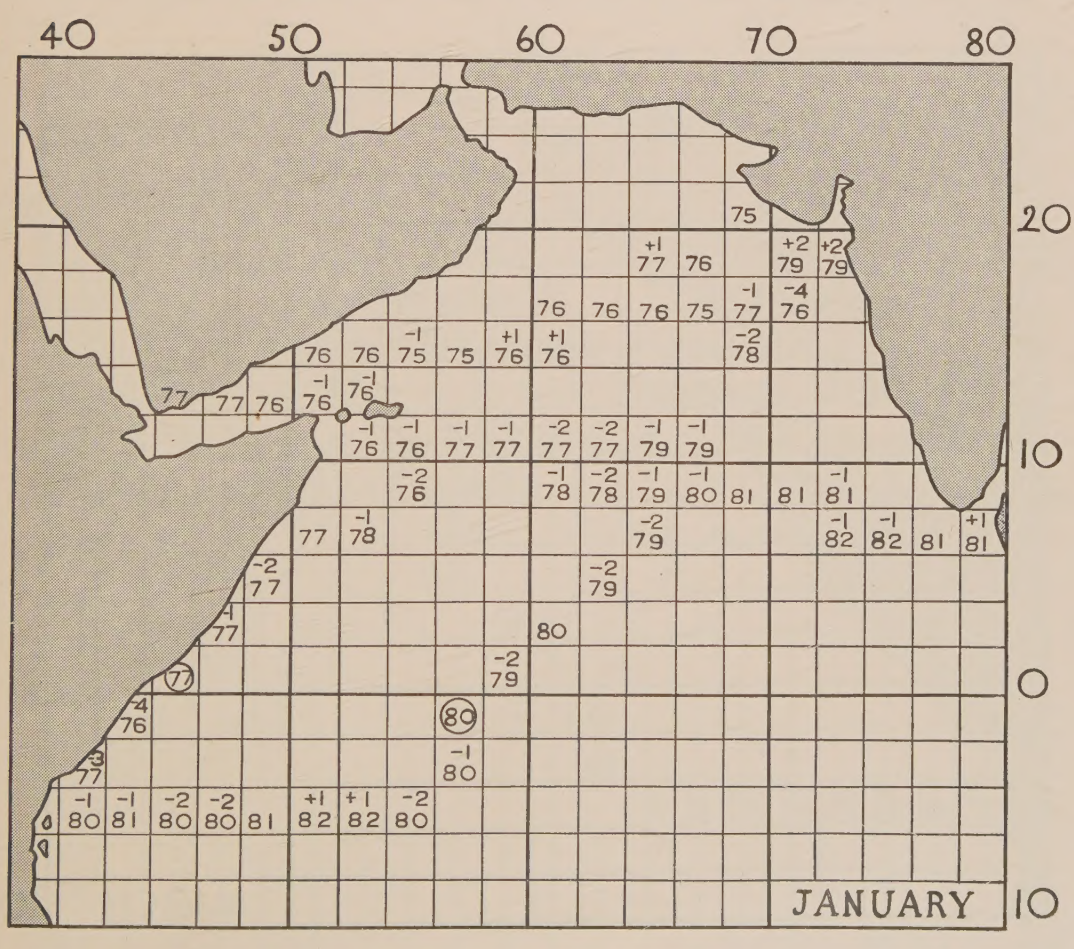
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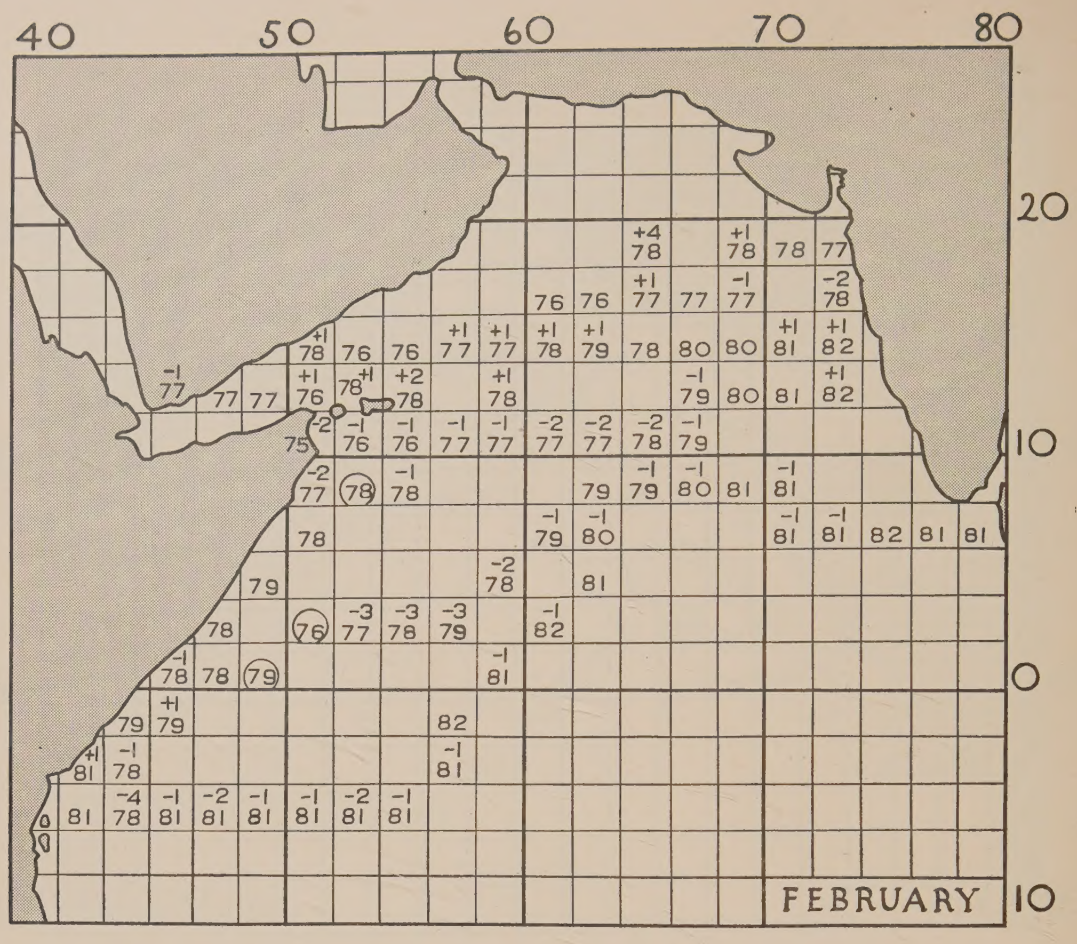
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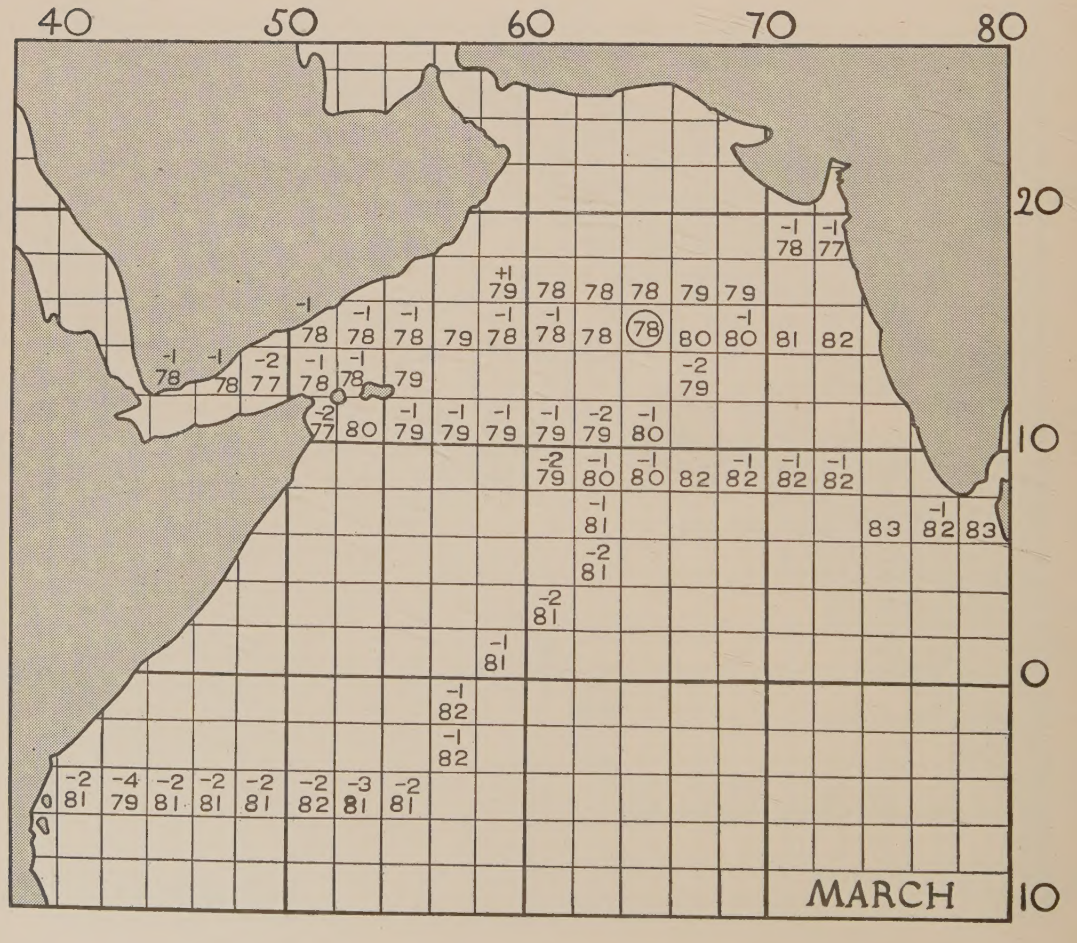
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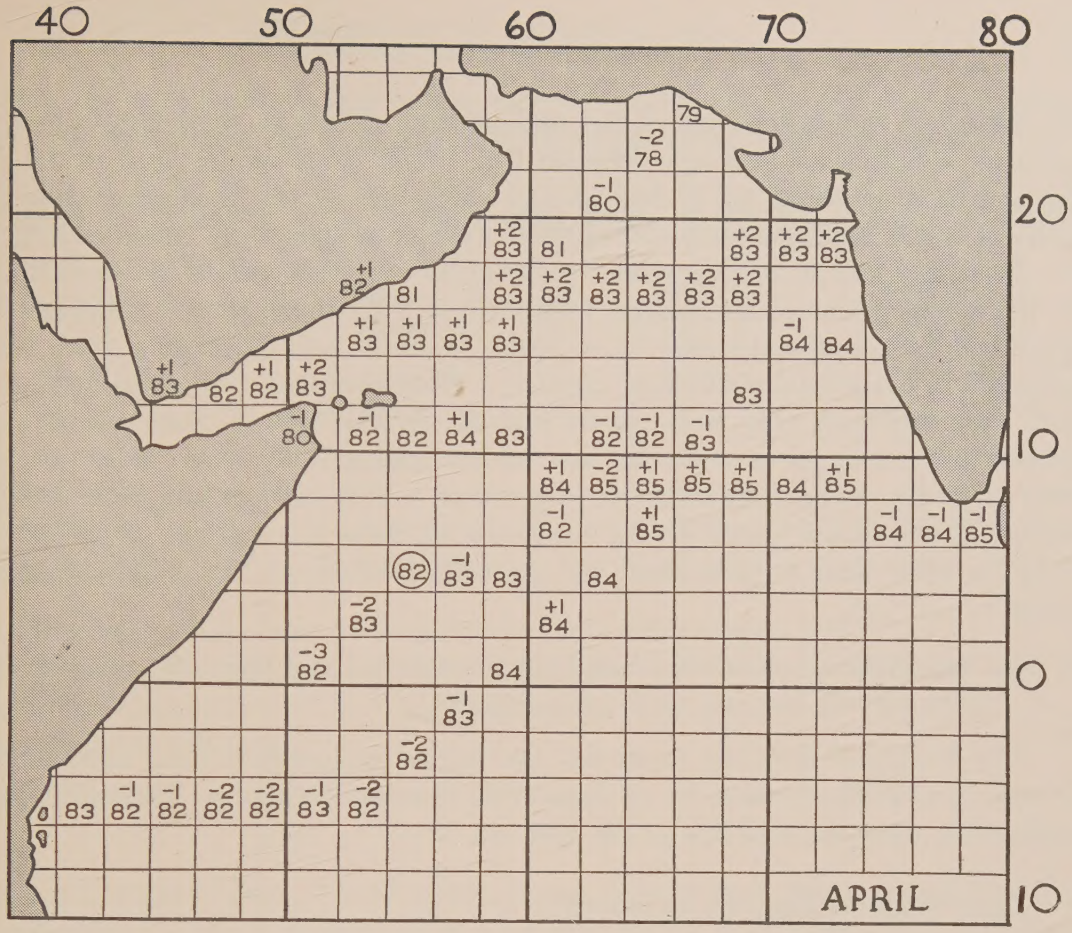
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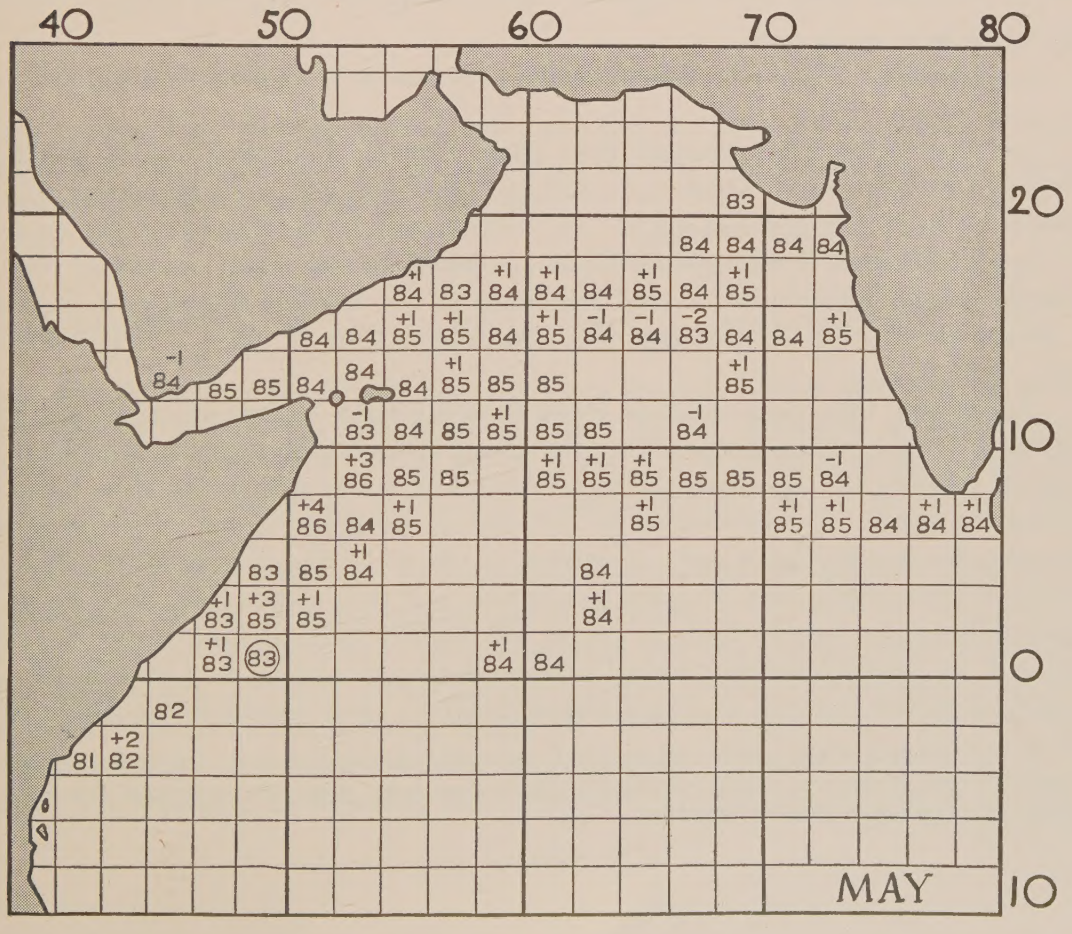
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the current in the western half of the Arabian Sea. The large difference in temperature normally obtaining in February between the colder waters at the head of the Arabian Sea and those at about 10° N. latitude, to which the reversal of current while the NE. monsoon is still blowing is attributed (Barlow, 1935), was apparently much reduced in 1934.

It is important to note here some results of Harvey (1925) which have a direct bearing on the measurement of sea surface temperatures. He shows that in quiet weather the upper inch or two of water may be so heated by solar radiation that a sharp surface of temperature discontinuity develops under it. It appears that this temperature distribution, once produced, may then persist through several days of rough weather, so that temperature observations made by the bucket method may give values considerably lower than the actual surface water temperature. This effect would be especially well marked in the Indian Ocean during the period of these observations (November–March or April), when there is little cloud and generally never more than a light to moderate breeze.

§4. The Diurnal Variation of Temperature of the Open Waters of the Arabian Sea.

The deviations from the mean day sea surface temperature have been determined for each hour of observation for 52 days of the five periods between December, 1933 and April, 1934, when the ship was in the open sea.

The averages of these are as follows :

	Hour.					
	4.	8.	12.	16.	20.	24.
Deviation from mean day temperature (° F.) .	−0·8	−0·1	+0·5	+0·6	+0·2	−0·7

An interesting point emerges from these figures. Following a very rapid fall in temperature between 20 hours and midnight, there is only a slight cooling of the sea surface between midnight and 4 a.m. On examination, it was found that the observations of the " Challenger " Expedition (Buchan, 1889) in the open waters of the North Atlantic (mean latitude 30° N. and longitude 42° S.) between March and August show a similar effect, with the corresponding hourly deviations of −0·3, −0·1, +0·2, +0·5, 0·0, −0·3.

It appears, then, that radiation losses from the water surface are small, and that the sudden fall in sea surface temperature after sunset is due mainly to losses from evaporation, assisted possibly by the mixing of upwelling colder water with the surface layer heated during the day.* An examination of the diurnal variation of the air temperature over the open sea (see §5) shows that, in contrast to the sea surface variation, the air temperature falls quite slowly from 20 hours to midnight and then very rapidly until 4 a.m. Thus evaporation from the sea surface will be but slightly reduced from sunset to midnight, but will be very effectively checked between midnight and 4 a.m. It will be observed also that cooling between 20 hours and midnight is much slower in the Atlantic than in

* The question of the relative efficiency of radiation and evaporation in cooling the sea surface has been examined by Harvey (1925), who finds that surface heat losses are influenced to a much greater extent by evaporation than by radiation.

the Arabian Sea, where all the observations were made during the period of the comparatively dry and very steady NE. monsoon—conditions producing great evaporation.

The mean temperatures and the mean daily range for the five cruises in question are :

Position.	Date. (1933).	Mean sea temperature (° F.).	Mean daily range (° F.).
81–86	2.xii–6.xii	80·0	1·4
91–102	14.xii–30.xii	79·5	1·4
	(1934.)		
127–129	31.i–5.ii	81·5	1·3
130–135	9.ii–21.ii	81·7	1·6
Colombo–173	20.iv–30.iv	84·0	2·3

For the whole period of the observations the mean daily range is 1·6° F.

The marked difference between the diurnal ranges in December–February and in April led to the examination of the daily variation for these two periods separately.

The respective values are :

December–February	−0·7	−0·1	+0·5	+0·5	+0·2	−0·6
April	−1·0	−0·1	+0·6	+1·0	+0·3	−0·8

The much greater range in April results almost entirely from the increased intensity of solar radiation. There *is* an increase in average humidity and decrease in wind speed, but both are so slight that the resultant decrease in evaporation is quite negligible.

§5. The Diurnal Variation of Air Temperature over the Open Sea.

The averages of the deviations from the mean day air temperature at each hour of observation have been calculated for 48 days when the ship was in the open sea, during periods between December and April. They are :

	Hour.					
	4.	8.	12.	16.	20.	24.
Deviation from mean (°F.)	−0·7	−0·2	+0·3	+0·7	0·0	−0·3

These deviations are considerably less than those given by Dallas (1894) for the same area and time of year. The corresponding values of the deviations obtained from Dallas's tables are −1·3, −0·1, +1·4, +1·3, −0·4, −0·9, while those of Buchan for 126 days in the open waters of the North Atlantic between March and August are −1·4, −0·2, +1·4, +1·6, −0·3, −1·0.

The disturbing effect of the ship on the surrounding air due to heating by solar radiation by day and cooling at night renders the observation of the true air temperature over the sea extremely difficult, and it seems probable that the greater deviations shown by Dallas, while partly the result of smoothing out in the process of averaging the present observations for different areas, is mainly due to differences in the mounting and screening of the thermometers. This radiation effect is particularly noticeable when the ship is stationary. For example, on February 3rd, 1934, when the ship was drifting in the open

sea (Station 128) and the wind 7 miles per hour with no appreciable change in direction, the air temperature rose by as much as 3·6° F. between 8 a.m. and noon. Again, during the night of April 23rd–24th, when the ship was carrying out hydrographic observations at Station 166 in a light wind, the temperature fell by 3·3° F. between midnight and 4 a.m., while, when the ship got under way again, the thermometer showed a rise in temperature of 3·7° F. by 8 a.m. Days showing such radiation effects to a marked degree were omitted when estimating the values given above.

These effects may persist, though in a much less degree, when the ship is in motion, so that it appears that the true diurnal variation of the air temperature over the open sea is normally very small—certainly less than would appear from observations aboard ship.

On the other hand, spindrift blown into the screen on to the thermometer bulb will cause the readings to be too low, but the conditions actually experienced in the open sea, the comparatively dry and seldom more than moderate breeze, would not be such as to make this effect appreciable.

Of course, since observations were made at 4-hourly intervals only, the actual thermometric range will be somewhat greater than the observed one. The " Challenger " 2-hourly observations showed that the minimum temperature occurred between 4 and 6 a.m. and the maximum at about 2 p.m., and Sewell (1927) observes that the average temperature at 4 p.m. is roughly ·2° F. lower than at 2 p.m. This correction is applied by him to determine the average daily range of temperature in the open waters of the Indian Seas. This is found to be 2·3° F. The present observations for the period December to April show an average daily range of 2·0° F. for all days when the ship was in the open sea—that is, an actual range of 2·2° F., assuming Sewell's correction. Buchan's " Challenger " observations are given for comparison :

Place.	Range (° F.).
South Atlantic	2·5
North Pacific	3·1
South Pacific	4·0
Atlantic (Equator)	2·6
Pacific (Equator)	2·1

The smaller diurnal range in air temperature in equatorial regions is explained by Buchan as being due to the greater average cloudiness in these areas.

The mean daily air temperature and daily range for each of the five cruises in the open sea is as follows :

Position (Stations).	Date (1933).	Mean temparature (° F.).	Mean daily range (° F.).
81–90	2.xii–7.xii	78	1·5
91–102	14.xii–30.xii	79	1·6
127–129	31.i–5.ii	81	2·0
130–135	9.ii–21.ii	81	2·0
Colombo–173	20.iv–30.iv	84	2·0

The Diurnal Variation of Air Temperature in Coastal Regions.

In contrast to the low values of daily range of air temperature over the open sea, the range in coastal areas may be very great. The average of the observed daily range on the cruise from Aden to Karachi along the Arabian coast was 5·4° F. The greatest daily range then observed was 9·8° F. on November 4th—apparently a cloudless day with a light wind; while the lowest was 3·0° F. on October 30th, when there was much cloud present and a moderate breeze blowing mainly off the sea.

In the Gulf of Aden on October 3rd, a range in air temperature of as much as 13·5° F. was observed.

§6. The Difference in Temperature Between the Surface of the Sea and the Overlying Air.

This is of decided importance from the point of view of local weather conditions, for a sea temperature below that of the overlying air results generally in the development of fog, while the reverse produces convection in the atmosphere.

It has to be borne in mind that the air temperature is determined on the deck of the ship, possibly some 15 to 20 feet above the sea level, by using a thermometer, effective screening of which is almost impossible; while sea temperatures obtained by the bucket method may give readings much below the actual surface temperature.

Considering the same 48 days as were used to estimate the diurnal variation of air temperature over the open sea (that is, omitting those showing marked radiation effects), an attempt was made to analyse the diurnal variation of the difference sea–air temperature. Though observations were for five cruises during periods from December to April, so that actual temperature differences varied for each,* a similar daily variation was evident throughout. The average for the five cruises is:

	Time.					
	4.	8.	12.	16.	20.	24.
Difference sea–air temperature (° F.)	+0·7	+0·7	+0·9	+0·5	+0·9	+0·5

The meaning of this diurnal variation is made clear by considering together the diurnal variation of sea and air temperature which are plotted on one graph.

Although readings at 4-hourly intervals necessarily give only a rough indication of the actual variation, they are sufficient to explain the above diurnal variation of the difference sea–air temperature.

* The mean temperature differences for the different areas and times are given here:

Dates.	Stations.	Average difference sea–air. (° F.).
2.xii–7.xii	82–90	1·6
14.xii–30.xii	92–102	0·5
31.i–5.ii	127–129	0·9
9.ii–21.ii	130–135	0·5
20.iv–30.iv	166–173	0·5

The large average difference at the head of the Arabian Sea is due to the comparatively low temperature of the air brought from the north by the monsoon.

It will be seen from the graph that—

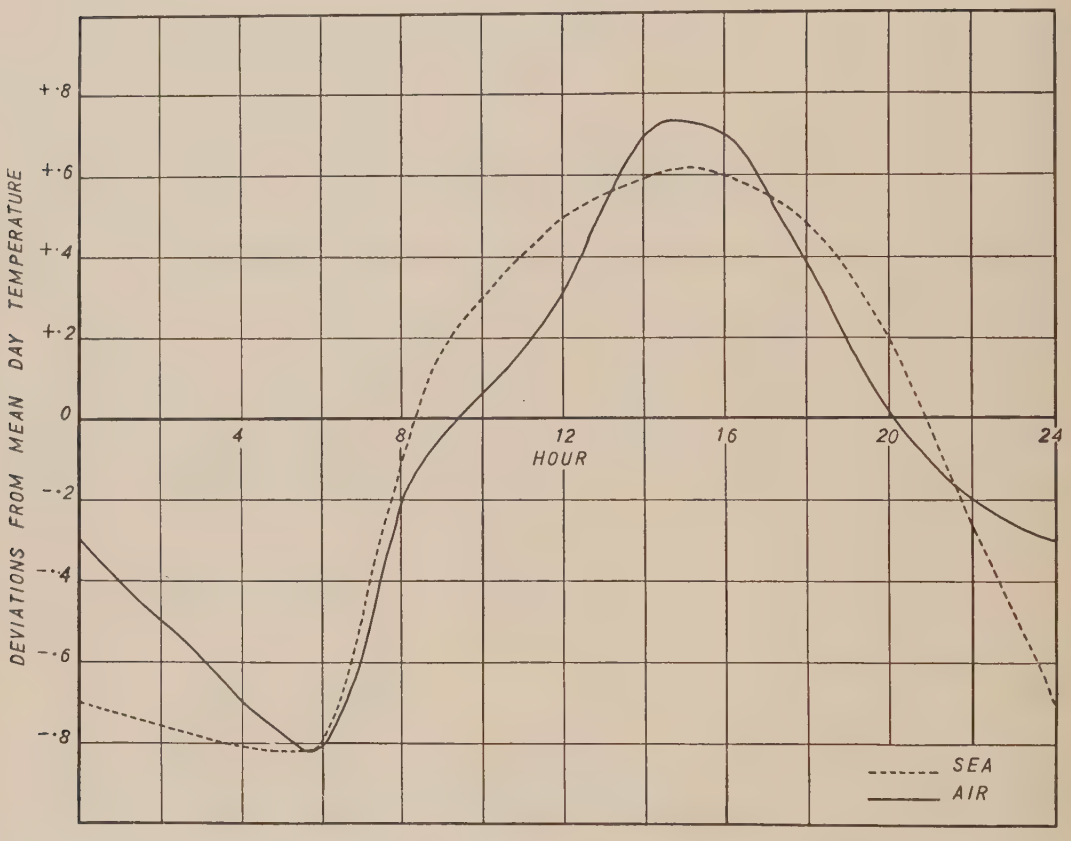
(*a*) From about 6 to 12 hours the sea by insolation increases in temperature more rapidly than the overlying air.

(*b*) From 12 to 16 hours the air temperature rises more rapidly than the sea surface temperature.

(*c*) From 16 to 20 hours the air temperature falls faster than the sea temperature.

(*d*) From 20 to 24 hours the sea surface cools more quickly than the air, and—

(*e*) From midnight to 4 hours the air temperature falls more rapidly than the sea.



Effects (*b*) and (*c*) must be exaggerated by and may even be due to errors introduced through the impossibility of effectively screening the air thermometer, which will certainly read higher than the actual air temperature round about noon and 14 hours. That is, the air thermometer will show a more rapid increase in temperature after about noon than is actually the case and, of course, a more rapid decrease when solar radiation falls off. Similarly, effect (*e*) must, at least in part, result from local radiation cooling, which causes the air thermometer to give readings below the true air temperature. Each of these effects will be particularly well marked when the sky is clear and the wind light. Effect (*d*) is due to the very rapid drop in sea surface temperature after sunset which we have already examined.

It would seem, then, that under the conditions obtaining between December and April in the open waters of the Arabian Sea, the temperature of the lower layers of air rises and falls at approximately the same rate as the sea surface temperature, but the matter can only be thoroughly examined by a consideration of the lapse rate of temperature above the sea.

Professor Brunt has called my attention to papers on vertical gradients of temperature in the lower layers of the atmosphere over the Baltic and Mediterranean Seas by Wüst (1920) and Johnson (1927) respectively.

Wüst arranged for observations of temperature by Assmann psychrometers to be made at different heights above the sea aboard a schooner (at heights of 9, 6, 4 and 2 metres), and on a dinghy situated about 150 metres from the schooner on the weather side (at heights of 0·2, 0·5, 1·2 and 2·0 metres). The local radiation effects outlined in paragraph 5 showed themselves clearly in the simultaneous readings at 2 metres on the schooner and dinghy. On the average, the temperature recorded at 2 metres on the schooner was 0·41° F. higher than on the dinghy, while in individual cases with bright sunshine, the difference was as high as 1·4° F. Examination of Wüst's temperature observations shows that (1) in bright weather the lapse rate in temperature up to the highest point of observation (9 metres) is very much in excess of the dry adiabatic lapse rate, and (2) in cloudy weather extremely high temperature gradients occur in the lowest metre, but above 6 metres the lapse rate decreases to approximately adiabatic. The air temperatures observed in cloudy conditions, when the radiation effect of the ship is much reduced, will approximate more closely to the true conditions, and the very large temperature gradient then observed near the surface emphasizes the influence of the sea in heating the air. Thus, in bright weather, the radiation from this small schooner (36 metres long, deck at $1\frac{1}{2}$ metres) affects the thermometer readings even at 9 metres and smooths out the super adiabatic lapse rate, so that it appears to persist slightly reduced up to a considerable height above the sea.

Johnson made careful observations of temperature gradient over the Mediterranean by platinum resistance thermometers carried at the mast-head (22 metres) and over the bows (5 metres). Observations were also made at 2 metres by lowering the forward element. His results are similar to those of Wüst, namely, a very high lapse rate near the surface falling slowly until at about 10 metres it becomes adiabatic.

It may be concluded that above a height of a few metres the lapse rate above the sea normally approximates to the dry adiabatic lapse rate.

Johnson finds that during the day the lapse rate between 5 and 22 metres is approximately the dry adiabatic, but that during the night it increases considerably. Assuming *no* diurnal variation of the sea temperature, he explains the increased lapse rate at night as due to the diurnal variation of air temperature (found to be 1·9° F.). The present observations in the Arabian Sea show that the sea temperature actually has a diurnal variation very similar to that of the overlying air, and the fact that the air temperature rises and falls at approximately the same rate as, and almost simultaneously with, the sea surface temperature appears to indicate that the diurnal variation of air temperature *is a result of* the diurnal variation of sea temperature.

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